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BIOMASS RETRIEVAL ALGORITHM BASED ON P-BAND BIOSAR EXPERIMENTS OF BOREAL FOREST

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ABSTRACT

A new biomass retrieval algorithm based on P-band multi-polarization backscatter has been developed and evaluated based on SAR and ground data over boreal forest. SAR data collections were conducted on three dates at a test site in southern Sweden (Remningstorp, biomass < 300 tons/ha; late winter to early summer 2007) and on a single date at a test site in northern Sweden (Krycklan, biomass < 200 tons/ha; fall 2008). The retrieval algorithm is a multiple linear regression model including the HV-polarized backscatter coefficient, the VV/HH backscatter ratio and the ground slope. Regression coefficients were determined from Krycklan data followed by algorithm evaluation using Remningstorp data. The results from the latter show that RMS errors vary in the range 29-42 tons/ha depending on date and stand type. The new algorithm is also compared with alternative algorithms and found to give significantly better performance. The developed model is a significant step towards an algorithm which gives consistent results across multiple sites and dates, i.e. when forest structure, topography and moisture conditions is expected to vary.

Index Terms— SAR, P-band, backscatter, biomass, boreal forest, retrieval algorithm, BioSAR, BIOMASS

1. INTRODUCTION

BIOMASS is one of three candidate missions for ESA's Earth Explorer 7 [1]. It consists of a P-band synthetic aperture radar (SAR) that will systematically acquire polarimetric and interferometric data over all major forested areas of the Earth [2]. Forest biomass is one of the most important parameters in the Earth's carbon cycle and, hence, for projections of future climate change. The present climate change is mainly due to fossil fuel burning and accumulation of CO2 in the atmosphere. However, it is also known that deforestation contributes with 10% to 30% of the total anthropogenic CO2 source. The large uncertainty is due to shortcomings in current observational techniques which is a strong motivation for implementing the BIOMASS mission.

The primary product of BIOMASS will be 100-m gridded maps of above-ground dry biomass covering the main forest biomes. Development of algorithms for estimation of forest biomass from P-band SAR is one of the most critical elements being addressed in phase A. The two main biomes considered are tropical and boreal forests. The algorithm development is being supported by airborne SAR data collections, i.e. BioSAR-1 in 2007 [3], BioSAR-2 in 2008 [4], and BioSAR-3 in 2010 [5] for boreal forests, and TropiSAR in 2009 [6,7] for tropical forests. E-SAR from DLR was used for BioSAR, whereas the SETHI SAR system from ONERA was used for TropiSAR. L-band data were also collected but not used in the present study.

The focus of the present paper is development and evaluation of biomass retrieval algorithms based on BioSAR 2007 and 2008. The results are hence mainly relevant for boreal forests. Furthermore, the paper does not include results using polarimetric interferometry.

2. BIOSAR EXPERIMENTS

BioSAR 2007 was conducted at Remningstorp in southern Sweden [3, 8-9]. It is a production forest with biomass up to 300 ton/ha on stand level. Topographic variations are overall small with an elevation range of only 20 m, but local ground slopes can be significant. The objectives of the experiment were to assess the potential for biomass estimation in (hemi)-boreal forests using P-band SAR and to study temporal decorrelation for polarimetric interferometry. The latter was addressed with three separate acquisitions from March to May. Results show that temporal correlation spanning two months from late winter to summer is adequate for repeat-pass interferometry [3].

BioSAR 2008 was conducted at Krycklan in northern Sweden [4, 10-11]. It is representative of higher latitude boreal forests and biomass varies up to 200 ton/ha on stand level. Topographic variations are higher than in Remningstorp, with ground elevation between 125 and 350 m. The objectives were slightly different compared to BioSAR 2007 and focused more on evaluating the effects of topography and multiple heading data were collected.

The dominant tree species for both sites are Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and birch

(*Betula spp.*). The SAR acquisitions were complemented by field measurements of forest parameters as well as high-density helicopter lidar data.

3. RETRIEVAL ALGORITHMS

In the past, a number of algorithms have been proposed and evaluated for forest biomass retrieval from P-band SAR data. We will use the six different regression models defined in Table 1. Small letters (a, b and c) with subscripts denote regression coefficients which are determined from training data. Above-ground dry biomass is denoted by W (tons/ha), and the backscattering coefficients, averaged over a stand and transformed to dB, are denoted by σ^o or γ^o. The two backscattering coefficients are related by $\gamma^o = \sigma^o - 10\log_{10}(\cos\theta_i)$, where θ_i is the local incidence angle. The backscattering coefficient γ^o includes normalization to compensate for the reduction of volume scattering as the incidence angle increases due to attenuation. The ground slope, i.e. the angle between surface normal and vertical, is denoted by u. θ is the nominal incidence angle (u = 0). C_0 (= 3.8914) and C_1 (= 0.1301) are constants defined in [12].

The first two algorithms are based on using HV backscatter only and have been derived from a number of data sets representing tropical, temperate and boreal forests [12-13]. The first model has only one regression coefficient, whereas the second model has two coefficients.

The third and fourth algorithms have been developed and evaluated based on data from Yellowstone [14]. The third algorithm includes both linear and quadratic terms in σ^o, i.e. in total seven coefficients. The fourth algorithm includes ground slope corrections, splits biomass into crown (W_c) and stem (W_s) biomass, and has fourteen coefficients.

The fifth algorithm is a modified version of an algorithm developed based on data from Alaska [15]. The latter contains additional terms, i.e. a second order term of the VV/HH ratio as well as first and second order terms of HH backscatter, which were dropped to make a comparison with the sixth algorithm easier. The sixth algorithm was developed based on BioSAR 2007 and BioSAR 2008 data. It includes the VV/HH ratio besides HV backscatter, as well as ground slope dependence. The total number of coefficients is six. The algorithm reduces to the fifth algorithm by excluding the three terms with ground slope dependency. As will be seen, the inclusion of VV/HH ratio and ground slope is important when applying the retrieval algorithms across multiple data sets.

4. BACKSCATTER AND BIOMASS OBSERVATIONS

SAR data have been calibrated to σ^o and γ^o using projection cosines determined from the imaging geometry and ground slope angles [16]. The latter were computed by least-squares fitting of a 50 m x 50 m plane centered on each pixel based on a 50-m grid DEM. Table 2 contains a summary of the SAR data collections during BioSAR 2007 and 2008.

Biomass was estimated on stand level. In Remningstorp, 10 (validation) stands based on field data only and 58 (training) stands based on field data, lidar and aerial photography are available. In Krycklan, 29 stands based on field data only are available. For details, see [3-4, 8-12].

Results from plotting all data points are shown in Fig. 1 for HV, HH and VV as well as the VV/HH ratio.

In Fig. 1a-b, scatter plots for HV and HH backscatter show a similar relationship with biomass but with a larger dynamic range for HH. For Remningstorp, HV and HH increases with biomass for the full biomass range. However, BioSAR 2008 data behaves differently, i.e. backscatter for a given biomass is generally lower than for BioSAR 2007. The main reason for this difference is likely due to the more pronounced topography in Krycklan.

In Fig. 1c, a scatter plot for VV shows little dependence between biomass and backscatter. VV backscatter for Remningstorp is also generally higher than for Krycklan for a given biomass, again likely caused by topographic effects.

Table 1. The six models relating above-ground dry biomass W (tons/ha) to P-band backscattering coefficients σ^o or γ^o (dB). Model 6 was developed for BioSAR 2007 and 2008.

#	Regression model function
1	$\log(W) = C_0 + C_1(\gamma^0_{HV} - a_0)$
2	$\log(W) = a_0 + a_1\gamma^0_{HV}$
3	$\log(W) = a_0 + a_1\sigma^0_{HH} + a_2(\sigma^0_{HH})^2 + a_3\sigma^0_{HV} +$ $+ a_4(\sigma^0_{HV})^2 + a_5\sigma^0_{VV} + a_6(\sigma^0_{VV})^2$
4	$\log W_c = a_0 + a_1\sigma^0_{HV}\cos(\theta-\theta_i) + a_2(\sigma^0_{HV}\cos(\theta-\theta_i))^2$ $+ a_3\sigma^0_{HH}\sin(\theta-\theta_i) + a_4(\sigma^0_{HH}\sin(\theta-\theta_i))^2$ $+ a_5\sigma^0_{VV}\cos(\theta-\theta_i) + a_6(\sigma^0_{VV}\cos(\theta-\theta_i))^2$ $\log W_s = a_0 + a_1\sigma^0_{HV}\sin(\theta-\theta_i) + a_2(\sigma^0_{HV}\sin(\theta-\theta_i))^2$ $+ b_1\sigma^0_{HH}\cos(\theta-\theta_i) + b_2(\sigma^0_{HH}\cos(\theta-\theta_i))^2$ $+ c_1\sigma^0_{VV}\cos(\theta-\theta_i) + c_2(\sigma^0_{VV}\cos(\theta-\theta_i))^2$
5	$\log(W) = a_0 + a_1\gamma^0_{HV} + a_2(\gamma^0_{VV} - \gamma^0_{HH})$
6	$\log(W) = a_0 + a_1 u + a_2\gamma^0_{HV} + a_3 u\cdot\gamma^0_{HV} +$ $+ a_4(\gamma^0_{VV} - \gamma^0_{HH}) + a_5 u\cdot(\gamma^0_{VV} - \gamma^0_{HH})$

Table 2. SAR data collections. Bold flight headings are primary headings; other headings do not cover all stands.

Campaign	Acquisition Date	Headings
BioSAR 2007	9 Mar, 31 Mar – 2 Apr, 2 May	179°, **200°**
BioSAR 2008	14 - 15 Oct	43°,**134°**,**314°**,358°

Figs. 1a-c show that backscatter from Remningstorp tends to decrease with time, i.e. from March to May 2007, which likely is caused by soil moisture conditions changing from wet to dry.

In Fig. 1d, a scatter plot for VV/HH ratio is shown. Contrary to HV, HH and VV, no clear difference between Remningstorp and Krycklan is observed and no systematic temporal change is observed showing that the VV/HH ratio is less affected by soil moisture and topography.

5. EVALUATION OF REGRESSION MODELS

The six regression models in Table 1 are evaluated by determining regression coefficients from BioSAR 2008 and evaluating root-mean-squared (RMS) errors from different parts of the BioSAR 2007 data set. The results, summarized in Table 3, show that algorithm 6 consistently gives significantly smaller RMS error compared to all other algorithms, in particular across multiple test sites and dates when structure, topography and moisture conditions vary.

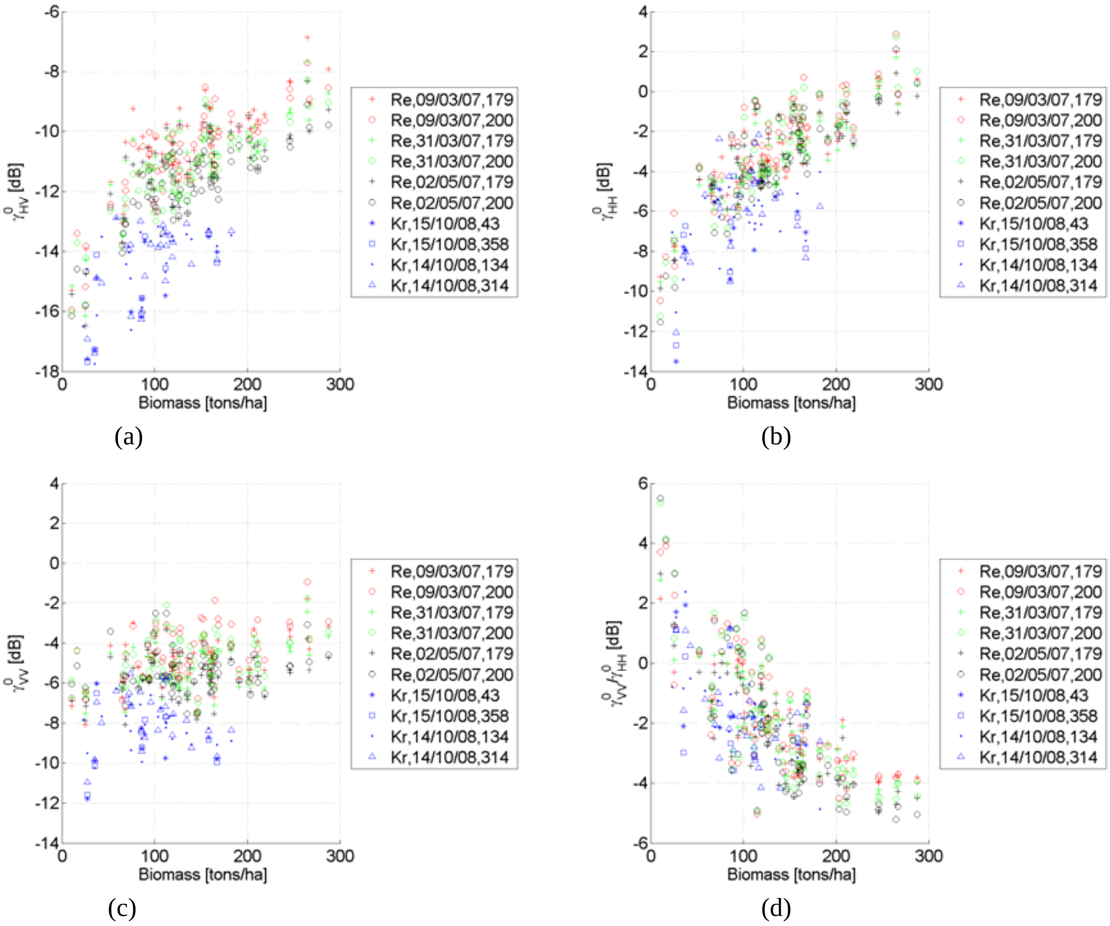

Fig. 1. P-band backscattering coefficient (γ^o) versus above-ground dry biomass for BioSAR 2007 (Re = Remningstorp) and BioSAR 2008 (Kr = Krycklan). The legends also include information about acquisition date and flight heading (deg).

4. SUMMARY AND CONCLUSION

A new biomass retrieval algorithm has been developed based on P-band SAR and ground data collected during BioSAR 2007 and 2008. The data sets include two boreal forest test sites in Sweden (Remningstorp, < 300 tons/ha; Krycklan, < 200 tons/ha) as well as multiple dates and flight headings. Results show that both topography and soil moisture affect P-band backscatter which should be taken into account in designing biomass algorithms. The new algorithm is a six-coefficient linear regression model including HV backscatter, VV/HH ratio and ground slope. The algorithm was evaluated by determining coefficients in Krycklan and evaluating RMS errors in Remningstorp. Results show that RMS residuals in Krycklan are 23-36 tons/ha, whereas RMS errors in Remningstorp are 29-42 tons/ha. Comparison with other algorithms shows significantly better results across multiple test sites and dates. It is concluded that the developed model produces consistent results with 20-30% RMS error of the mean biomass.

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Table 3. RMS residuals and error from evaluating six regression models in Table 1. Models were trained in Krycklan (lowest four rows therefore give RMS residuals) and validated in Remningstorp (six top rows give RMS errors).

Test Site	Stand Type	Acquisition Month	Flight Headings	RMSE [tons/ha]					
				Alg. 1	Alg. 2	Alg. 3	Alg. 4	Alg. 5	Alg. 6
Remningstorp	Training	March 2007	179°, 200°	161.8	102.5	99.2	103.5	58.6	33.2
Remningstorp	Training	April 2007	179°, 200°	116.3	74.4	90.4	96.4	45.8	29.2
Remningstorp	Training	May 2007	179°, 200°	95.3	62.7	76.2	81.6	48.3	31.2
Remningstorp	Validation	March 2007	179°, 200°	235.4	127.1	163.0	165.0	73.6	35.1
Remningstorp	Validation	April 2007	179°, 200°	164.1	86.4	149.2	154.1	62.5	38.1
Remningstorp	Validation	May 2007	179°, 200°	120.2	64.8	126.4	129.4	62.3	42.4
Krycklan	All	October 2008	43°	36.3	36.5	21.9	30.0	30.2	23.6
Krycklan	All	October 2008	134°	34.3	33.7	22.9	29.1	25.9	23.1
Krycklan	All	October 2008	314°	34.8	34.0	25.4	27.4	30.7	27.4
Krycklan	All	October 2008	358°	40.1	40.0	29.5	33.5	37.8	36.1